Emerging Evidence on COVID-19

Evidence Brief on Aerodynamic Analysis and Aerosolization of SARS-CoV-2

Introduction

What aerodynamic properties of SARS-CoV-2 virus and travel distance are reported within the emerging literature, and what are the implications of this evidence on transmission risk?

The majority of COVID-19 infection control measures, including social distancing, community masking, respiratory etiquette, and hand hygiene, have focused on infection transmission due to respiratory droplets, as well as close proximity to infected individuals or contaminated surfaces. Virus particles in small droplets and aerosols can also influence infection risk via airborne transmission. Airborne transmission occurs when an infectious agent is carried by dust or droplet nuclei (dried residue <5 microns) that can be suspended in the air and may be blown large distances, which is in contrast to droplets that usually fall to the ground in within a few feet (Remington et al, 1985). This evidence brief highlights specific literature on aerosolization and aerodynamics of SARS-CoV-2 published until July 6, 2020.

Key Points

- Epidemiological investigations of COVID-19 clusters in public settings, including department stores, choir practice, airplanes, buses and restaurants have attributed infections, at least partially, to airborne transmission (Table 3).
- A quantitative risk analysis using two COVID-19 clusters attributed to a restaurant and a choir practice, concludes the high attack rates observed in both outbreaks can only be possible if airborne transmission is the assumed primary mode of transmission (Buonanno, Morawska, & Stabile, 2020).
- There are no studies that estimate SARS-CoV-2 infection transmission risk based on varied distance from an infectious source, or evaluate factors impacting airborne transmission on the virus. There is limited evidence on virus viability in expelled particles or the infectious dose.
- van Doremalen provides experimental evidence to support the viability of SARS-CoV-2 virus particles in aerosols. The study reports SARS-CoV-2 virus can remain viable within aerosols for longer than three hours (van Doremalen et al., 2020).
- Mathematical models informed by the laws of particle physics and aerodynamics predict airborne particles can remain suspended in air for long enough to be inhaled and have the potential to be dispersed some distance away from the infectious source (Feng, Marchal, Sperry, & Yi, 2020; Guerrero, Brito, & Cornejo, 2020; Vuorinen et al., 2020; Zhao, Qi, Luzzatto-Fegiz, Cui, & Zhu, 2020).

- According to mathematical models, droplet size, humidity, temperature, air flow, and air turbulence all impact the travel distance and decay of virus containing airborne particles. Key findings from individual studies (Table 1).
- Simulation studies find thousands of minute respiratory droplets and aerosols are generated when speaking, and these particles can remain suspended in air for periods longer than eight minutes (Anfinrud, Bax, Stadnytskyi, & Bax, 2020; Stadnytskyi, Bax, Bax, & Anfinrud, 2020).
- Multiple researchers have investigated the presence of SARS-CoV-2 laden aerosols in air sampled from various healthcare environments managing COVID-19 patients (Table 2).

Overview of the Evidence

Publications appearing in the emerging literature up to July 7, 2020 have informed this evidence brief. The available body of evidence is limited, largely theoretical, and does not specifically consider SARS-CoV-2 infectious dose or confirm the infectiousness of airborne particles. The theoretical and modeling evidence is of good quality. The available empirical and modeled evidence indicates there is some risk of SARS-CoV-2 virus laden aerosol and droplet dispersion at distances beyond two meters, while epidemiological evidence implicates airborne transmission of SARS-CoV-2 to have occurred in some indoor settings. Airborne infection transmission risks appear to be amplified in low temperature high humidity conditions, as well as in crowded and poorly ventilated areas where infected individuals may cough or speak loudly (i.e. sing, scream).

CONTENTS

SARS-COV-2 SUSPENDEND AEROSOLS (AIR)

Airborne SARS-CoV-2 particles exist in the form of aerosols, small droplets, droplet nuclei, micro droplets or other small particles containing viral RNA. One experiment has reported the viability of SARS-CoV-2 virus particles in aerosols (van Doremalen et al., 2020). The study reports SARS-CoV-2 virus can remain viable within aerosols for longer than three hours.

Two simulation studies find thousands of minute respiratory droplets and aerosols are generated when speaking, and these particles can remain suspended in air for periods longer than eight minutes (Anfinrud, Bax, Stadnytskyi, & Bax, 2020; Stadnytskyi, Bax, Bax, & Anfinrud, 2020). Two others investigate droplets and aerosols resulting from breathing and coughing (Viola et al., 2020;Rodriguez-Palacios, Cominelli, Basson, Pizarro, & Ilic, 2020).

Five mathematical models informed by the laws of particle physics and aerodynamics predict these particles can remain suspended in air for long enough to be inhaled and have the potential to be dispersed some distance away from the infectious source (Feng, Marchal, Sperry, & Yi, 2020; Guerrero, Brito, & Cornejo, 2020; Vuorinen et al., 2020; Zhao, Qi, Luzzatto-Fegiz, Cui, & Zhu, 2020; Blocken, Malizia, van Druenen, & Marchal, 2020). According to mathematical models, droplet size, humidity, temperature, air flow, and air turbulence all impact the travel distance and decay of virus containing airborne particles. Key findings from individual studies (Table 1). Models predict small droplets and aerosols can travel distances as far as ten meters when generated by coughs or sneezes. As a result the recommendation of two meters distance may not be sufficient to negate aerosolized SARS-CoV-2 transmission (Feng et al., 2020; Guerrero et al., 2020; Zhao et al., 2020). Speed of movement also impacts droplet travel distance. Computer fluid dynamic simulations find, although a distance of 1.5 meters may be a protective distance when standing still, distances greater than 1.5 meters are necessary when two individuals are running or moving fast as inertia of expelled droplets also impacts droplet spread (Blocken, Malizia, van Druenen, & Marchal, 2020). Low temperature and high humidity are found to facilitate respiratory droplet transmission and dispersion, while high temperature and low humidity promotes the rapid loss of respiratory droplet mass (from evaporation) thereby reducing droplet travel distance (Feng et al., 2020; Zhao et al., 2020). A 3D simulation demonstrates SARS-CoV-2 aerosols can travel distances up to ten meters, and the inhalation of sufficient concentrations of aerosols (100 particles was considered an infectious dose in this study) is possible within time periods that range from one second to one hour (Vuorinen et al., 2020).

Table 1: Primary literature on SARS-CoV-2 suspended aerosols and particle dispersion distance

Publication Title	Key Outcomes	Reference
Experimental and Simulation Studies		
Could SARS-CoV-2 be Transmitted via Speech Droplets?	A planar beam of laser light passing through a dust-free enclosure is used to detect saliva droplets emitted while speaking. The experimental setup detects hundreds of	(Anfinrud et al., 2020)

	respiratory and saliva droplets being emitted during normal speech and coughing. The investigation provides visual evidence infection transmission from droplets and aerosols is possible. These are preliminary findings and researchers state additional studies are necessary to assess the viral titer present in speech-induced droplets based on COVID-19 severity.	
Textile Masks and Surface Covers- A Spray Simulation Method and a "Universal Droplet Reduction Model" Against Respiratory Pandemics	Dispersion distances of respiratory droplets when wearing face coverings made of common household materials was measured using a bacterial-suspension spray simulation (mimicking a sneeze). Most bacteria-carrying droplets landed within 1.2 meters of the source with a textile mask compared to droplet travel distances of greater than 1.8 meters when no barriers (meant to mimic no face covering) were in place.	(Rodriguez-Palacios, Cominelli, Basson, Pizarro, & Ilic, 2020)
The Airborne Lifetime of Small Speech Droplets and Their Potential Importance in SARS-CoV-2 Transmission	Laser light scattering experiments are enlisted to visualize droplet dispersion and decay. The experiments find droplets generated during normal speech to decay within 8-14 minutes in close stagnant environments (similar to indoor environments, particularly with poor ventilation), and the longest decay times were observed for droplets with a diameter ≥12 µm when exiting the mouth. The researchers estimate 1 min of loud speaking can generate a minimum of 1,000 virion containing droplet nuclei that remain airborne for more than 8 minutes. The findings suggest air suspended virus containing particles could be inhaled by others.	(Stadnytskyi et al., 2020)
Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1	The stability and decay of SARS-CoV-2 and SARS-CoV-1 in aerosols was estimated using a Bayesian regression model SARS-CoV-2 virus remained viable in aerosols up to 3 hours (duration of the experiment), with a reduction in infectious titer from $10^{3.5}$ to $10^{2.7}$ $TCID_{50}$ per liter of air.	(van Doremalen et al., 2020)
Face Coverings, Aerosol Dispersion and Mitigation of Virus Transmission Risk	Researchers use a background oriented Schlieren technique to visualize airflow and investigate the effectiveness of different face covers in mitigating aerosol dispersion during breathing and coughing. The study reports a thermal plume containing respiratory particles were visible at distances less than 0.5 meters during normal breathing simulated by human subjects and manikins. Thermal plume were visible approximately 1.1 meter away from the source mouth during manikin generated coughing.	(Viola et al., 2020)

Publication Title	**Key Outcomes**	**Reference**
Mathematical Models		
Towards Aerodynamically Equivalent COVID19 1.5 m Social Distancing for Walking and Running	Computer Fluid Dynamics study informed by previous data on droplet dispersion around a runner takes into account the potential aerodynamic effects introduced by a person movements (e.g., walking fast, running and cycling) on droplet travel distance. The study investigates whether a leading infectious person standing still and moving nearby a second susceptible person at a distances of 1.5 meters or more can pose any infection transmission risk. Although particle exposure is negligible when two people are standing 1.5 meter apart, if the individuals are running or walking fast even at 1.5 meters apart there is some risk of infectious particle exposure. The study results suggest the greatest exposure to the trailing person occurs if they are directly behind the leading person (positioned in the slipstream). Substantial droplet exposure risk reduction can be achieved by 1) avoiding to walk or run in the slipstream of the leading person, 2) keeping the 1.5 m distance in staggered or side by side arrangement, or 3) by keeping social distances greater than 1.5 meters when moving fast or running.	(Blocken et al., 2020)
Quantitative Assessment of the Risk of Airborne Transmission of SARS-CoV-2 Infection: Prospective and Retrospective Applications	A quantitative risk assessment based on analysis of restaurant outbreaks in Guangzhou, China and the Choir practise in Skagit County, US (Table 2) find the high attack rates in both cases are only plausible if airborne transmission is the primary route of transmission.	(Buonanno et al., 2020)
Influence of Wind and Relative Humidity on the Social Distancing Effectiveness to Prevent COVID-19 Airborne Transmission: A Numerical Study	Air transmission of cough droplets with condensation and evaporation effects are modeled between two virtual humans under different environments and wind velocities. Micro-droplets follow airflow streamlines and can be deposited on virtual human bodies (including head regions) at greater than 3.05 meter (10 feet) distances. High relative humidity (99.5%) also leads to larger droplet sizes and greater deposition of cough droplets on surfaces (due to hygroscopic growth effects). Suspended micro-droplets could be transmitted between the 2 virtual humans in less than 5 seconds.	(Feng et al., 2020)

	The study concludes, that due to environmental wind, convection effects and relative humidity on respiratory particles emitted by humans, the frequently recommended 1.83 meters (six feet) of social distancing may not be sufficient to prevent inter-person aerosol transmission.	
COVID-19. Transport of Respiratory Droplets in a Microclimatologic Urban Scenario	Examined the spread of respiratory droplets in outdoor environments by applying a computational model of a sneezing person in an urban scenario under a medium intensity climatological wind. The spread of respiratory droplets is characterized by the dynamics of droplet size: larger droplets (400 – 900μm) are spread between 2-5 meters during 2.3 seconds while smaller droplets (100 – 200μm) are transported between eight and eleven meters in 14.1 seconds when influenced by turbulent wind.	(Guerrero et al., 2020)
Modelling Aerosol Transport and Virus Exposure with Numerical Simulations in Relation to SARS-CoV-2 Transmission by Inhalation Indoors	Available evidence on aerosol transport in air is combined with dimensional simulations in physics-based models and theoretical calculations. Monte Carlo simulations indicate droplets produced by speech and cough (diameter < 20 μm) can become airborne and linger in air from 20 minutes up to 1 hour, and be inhaled by others. The exposure time to inhale 100 aerosols (assumed to be an adequate infectious dose) is variable based on the situation and can range from one second, to 1 minute, to 1 hour. 3D computational fluid dynamic (CFD) simulations suggest aerosols (dp <20 μm) can be transported over 10 meter distances in generic environments, dependent on relative humidity and airflow. Finally the rapid drying of expelled mucus droplets would yield droplet nuclei and aerosols which could potentially carry airborne virus particles. Such droplets (initial particle diameter of 50 μm to 100 μm) could remain airborne for approximately 20 seconds to 3 minutes.	(Vuorinen et al., 2020)
COVID-19: Effects of Weather Conditions on the Propagation of Respiratory Droplets	A comprehensive mathematical model to explore speech generated droplet evaporation, heat transfer and kinematics under different conditions (e.g., temperature, humidity and ventilation). Findings include that low temperature and high humidity facilitate droplet transmission and dispersion, but supresses the formation of aerosols. On the other hand, high temperature and low humidity promotes rapid loss of respiratory droplet mass (from evaporation) and reduces droplet travel distance but these conditions increase transmission risk from	(Zhao et al., 2020)

	aerosol particles. The study concludes current social distancing recommendations may not be sufficient to diminish all airborne transmission risks as droplets can travel distances up to 6 meters in some conditions.	

COVID-19 PRESENCE IN AIR SAMPLES

Seven studies have investigated the presence of SARS-CoV-2 laden aerosols in air sampled from various healthcare environments managing COVID-19 patients (Table 2). The presence of SARS-CoV-2 in air samples from real-world settings is variable, but there appears to be a connection between air contamination and poor ventilation. (Ding et al., 2020; Y. Liu et al., 2020; D. Zhang et al., 2020). Air samples containing SARS-CoV-2 viral RNA have been detected further than two meters, and as far as four meters from infected patients (Ding et al., 2020; Guo et al., 2020; Y. Liu et al., 2020; Nissen et al., 2020; Santarpia et al., 2020). Across studies, the majority of air samples from healthcare settings are SARS-CoV-2 negative, suggesting air ventilation and filtration strategies employed by hospitals to maintain high air quality effectively reduce airborne transmission risk in healthcare settings.

Table 2: Primary literature of field studies evaluating SARS-CoV-2 contamination of air samples

Publication Title	Key Outcomes	Reference
SARS-CoV-2 Spillover into Hospital Outdoor Environments	Viral RNA contaminated aerosols were identified in waste water treatment areas and a hospital entrance receiving confirmed cases, in Wuhan China. These findings indicate airborne virus can be present in hospital outdoor environments, specifically within medical wastewater treatment facilities and spaces occupied by SARS-CoV-2 infected patients.	(D. Zhang et al., 2020)
Toilets Dominate Environmental Detection of SARS-CoV-2 Virus in a Hospital	A single air sample from a hospital corridor was weakly positive for SARS-CoV-2 virus. All other tested air samples from patient rooms, washrooms, and air supply inlets were negative.	(Ding et al., 2020)
Aerosol and Surface Distribution of Severe Acute Respiratory Syndrome Coronavirus 2 in Hospital Wards, Wuhan, China, 2020	35% of air samples collected from hospital ICU and general wards in Wuhan, China tested positive for SARS-CoV-2 virus particles. Positive samples were identified near air outlets (35.7%), patient rooms (44.4%) and physician offices (12.5%). Virus-laden samples were most often identified downstream from COVID-19 patients.	(Guo et al., 2020)

	In the ICU ward space, patient care and treatment areas were positive for SARS-CoV-2 virus aerosols, and positive samples were identified up to 4 meters from the COVID-19 patient. In the general ward space, areas positive for SARS-CoV-2 were within 2.5 meters upstream of the patient. No SARS-CoV-2 virus aerosols were identified in patient corridor areas. Based on their findings on SARS-CoV-2 aerosol spatial distribution, the authors conclude maximum aerosol transmission distance to be approximately 4 meters.	
Long-Distance Airborne Dispersal of SARS-CoV-2 in COVID-19 Wards	SARS-CoV-2 RNA was detected in and near air vent openings of COVID-19 isolation rooms of a hospital ward, and on filters and fluid sample collected from the ventilation system at the top of the hospital building. These findings suggest aerosol dispersion of SARS-CoV-2 and long-distance dissemination of SARS-CoV-2 via ventilation airflow can occur.	(Nissen et al., 2020)
Air, Surface Environmental, and Personal Protective Equipment Contamination by Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) From a Symptomatic Patient	No air samples from patient airborne infection isolation rooms (AIIR) housing 3 symptomatic confirmed cases of COVID-19 were positive for SARS-CoV-2 virus.	(Ong et al., 2020)
Aerosol and Surface Transmission Potential of SARS-CoV-2	Air and surface samples from isolation spaces housing COVID-19 cases in the United States were collected and tested for SARS-CoV-2 viral RNA. High volume air samples and low volume personal air samples were tested for SARS-CoV-2 presence by RT-PCR. 63.2% of air samples from patient isolation areas were positive for viral RNA, and 58.3% of air samples from hallways outside of patient isolation areas were also positive for the virus. Viable virus was not recovered. The findings suggest viral aerosol particles can be produced by infected individuals even during the absence of cough, and travel distances greater than 6 feet (1.8 meters).	(Santarpia et al., 2020)

Aerodynamic analysis of SARS-CoV-2 in two Wuhan hospitals	SARS-CoV-2 RNA concentrations in aerosol samples from Wuhan, China hospital settings were quantified. Sampled environments include patient care, public and staff areas within or near a hospital, and field hospital settings. Patient care areas SARS-CoV-2 concentrations within suspended aerosols sampled from hospital patient care environments were very low to undetectable, suggesting the effectiveness of negatively pressurized isolation and frequent air exchanges in hospital environments. In the field hospital setting, the greatest SARS-CoV-2 concentrations within suspended aerosols were identified in a temporary patient toilet room (1 m^2 area) with low ventilation. Public areas Low to undetectable SARS-CoV-2 concentrations were identified for the majority of suspended aerosols from sampled public areas. However, virus concentrations (>3 copies m^{-3}) were detected in 2 public sites, a department store entrance and an outdoor site near the hospital. Results suggest high traffic flow and crowding may play a role in elevating virus concentrations in aerosol suspensions. Exclusively healthcare worker staff areas Highest SARS-CoV-2 concentrations were observed in staff personal protective equipment removal and changing rooms in the field hospital. Based on the size ranges of SARS-CoV-2 aerosols (submicron region (dp between 0.25 to 1.0 µm), supermicron region (dp > 2.5 µm)), virus concentrations and aerosol size distribution within these areas, the authors hypothesize the observed high concentrations are due to resuspension of virus containing aerosols from healthcare worker PPE surfaces and apparel.	(Y. Liu et al., 2020)

COVID-19 CLUSTERS ATTRIBUTED TO AIRBORNE TRANSMISSION

Eight studies on clusters of COVID-19 cases attributed at least partially to airborne transmission. Two of these outbreaks have been reported and then further analyzed with computer simulations to explore the likelihood and characteristics of the setting that lead to transmission (Hamner et al., 2020;Miller et al., 2020; Li et al., 2020; Lu et al., 2020). The other outbreak investigations report that airborne transmission is suspected to have occurred based on the findings of the retrospective investigation, however, due to the nature of these studies, this cannot be proven.

Table 3: Primary literature on Epidemiological investigations that (partially) attribute clusters to airborne Transmission

Publication Title	Key Outcomes	Reference
High SARS-CoV-2 Attack Rate Following Exposure at a Choir Practice — Skagit County, Washington, March 2020 AND Transmission of SARS-CoV-2 by Inhalation of Respiratory Aerosol in the Skagit Valley Chorale Superspreading Event.	A choir practice in Washington, US involving 61 singers, including the symptomatic index case, led to 32 confirmed and 20 probable secondary COVID-19 cases (attack rate = 53.3% to 86.7%); 3 patients were hospitalized, and 2 died. Authors conclude transmission was likely facilitated by close proximity (within 6 feet) during singing practice and augmented by the act of singing.	(Hamner et al., 2020; Miller et al., 2020)
COVID-19 Outbreak Associated with Air Conditioning in Restaurant, Guangzhou, China AND Evidence for Probable Aerosol Transmission of SARS-CoV-2 in a Poorly Ventilated Restaurant	Droplet transmission at distances less than 1 meter are considered to be the primary mode of transmission for a cluster (n=10) linked to dining at a restaurant. Families A, B, and C with confirmed COVID-19 cases had not met previously and did not have close contact during the lunch, aside from some patrons sitting back-to-back. However, aerosol transmission is not ruled out due to the <1 meter distance separating some of the cases. Computer simulations of fine exhaled droplets and the investigation of video footage by Li et al., demonstrate transmission pattern among the cases are consistent with airborne transmission.	(Li et al., 2020; Lu et al., 2020)
Airborne Transmission of	The risk of airborne transmission is considered for 2 independent COVID-19 clusters, one involving bus riders to and	(Shen et al., 2020)

COVID-19: Epidemiologic Evidence from Two Outbreak Investigation	from a worship event (n=126), and another involving a 3 day conference workshop. Based on the relative risk of infection among bus riders and the attack rate for the workshop outbreak, the investigators conclude airborne spread may have played a role in both exposure events.	
Analysis on cluster cases of COVID-19 in Tianjin	Describes various COVID-19 clusters in Tianjin City, China associated with the high possibility of airborne infection transmission within indoor settings. Infection transmission in aircrafts, train carts, department stores, and workplace settings (this cluster is individually reported on by Zhan et al., above) is investigated.	(Y. F. Liu et al., 2020) Original article not English
Epidemiological investigation on a cluster epidemic of COVID-19 in a collective workplace in Tianjin	COVID-19 outbreak in an administrative office of a plant. Epidemiological analysis suggests the index case transmitted the infection to ten other coworkers, prior to control measures being put in place. All cases were found have travelled with, participated in meetings, or sat near other infected co-workers.	(Y. Zhang et al., 2020) Original article in Chinese
In-flight Transmission Cluster of COVID-19: A Retrospective Case Series.	A cluster of airplane passengers (n=12) provide evidence of inflight transmission of infection.	(Yang et al., 2020)

Methods:

A daily scan of the literature (published and pre-published) is conducted by the Emerging Science Group, PHAC. The scan has compiled COVID-19 literature since the beginning of the outbreak and is updated daily. Searches to retrieve relevant COVID-19 literature are conducted in Pubmed, Scopus, BioRxiv, MedRxiv, ArXiv, SSRN, Research Square and cross-referenced with the literature on the WHO COVID literature list, and COVID-19 information centers run by Lancet, BMJ, Elsevier and Wiley. The daily summary and full scan results are maintained in a Refworks database and an excel list that can be searched. Targeted keyword searching is conducted within these databases to identify relevant citations on COVID-19 and SARS-COV-2. Search terms used included: aerosol, droplet

Each potentially relevant reference was examined to confirm it had relevant data and relevant data is extracted into the review. This review contains research published up to July 7, 2020.

Prepared by: Chatura, Prematunge. Emerging Science Group, PHAC. phac.emergingsciencesecretariat-secretariatdessciencesemergentes.aspc@canada.ca

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